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Effect of Soil Amendments Derived from Agricultural Biomass on Rice Yield and Soil Fertility in a Paddy Field of South Korea †

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Abstract: The objective of this study was to compare the effects of biochar and straw applications on rice yield and soil fertility during a three-year period. The three treatment conditions were: BC (2000 kg ha^{-1} of barley straw biochar), BS (2000 kg ha^{-1} of barley straw), and BC + BS (1000 kg ha^{-1} of barley straw biochar + 1000 kg ha^{-1} of barley straw, respectively). Each treatment area was separated by an untreated control (CN) area. During the study, the rice yields for CN, BC, BS, and BC + BS treatments ranged on average from 473 to 515, 497 to 532, 516 to 528, and 583 to 602 g m^{-2}, respectively. Among the treatments, the BC + BS treatment produced the highest average rice yield, which was stable during the three-year study. The soil changes after the final rice harvesting were different in the BC and BS application areas. Soil bulk density and pH were improved in all treatments except for the CN treatment compared to those of raw soil. The SOC and TN content after the BC application increased by 0.56 and 0.08 g kg^{-1}, respectively, compared to those of the CN soil, while those after the BS and BC + BS applications increased by 0.89–1.36 and 0.16–0.3 g kg^{-1}, respectively. The soil CEC values after the BC, BS, and BC + BS treatments were 0.55, 0.37, and 0.49 cmol$_c$ kg^{-1} higher than those in the CN, respectively. Therefore, such an approach can reduce the application of inorganic fertilizer, thereby encouraging the development of sustainable organic agriculture.

Keywords: rice yield; soil fertility; barley straw; barley straw biochar; sustainable organic agriculture

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1. Introduction

Rice is the most important, major food resource in most Asian countries including South Korea. However, the rice cultivation area is decreasing because rice prices have fallen after the rice tariffication law [1]. As a result, rice production in South Korea was 14.6% lower in 2016 than that in 2009. In addition, environmental problems in agriculture are increasing in seriousness due to the excessive use of inorganic fertilizers, strong rainfall in the summer, and frequent tilling, which have together led to a deterioration in the physical properties of the soil and increased CH_4 and N_2O emissions [2,3]. To overcome this issue, researchers have studied the application of related organic materials such as straw, green manure crops, and compost, but there has been little research on the use of biochar in South Korea.

Biochar is a material obtained after pyrolyzing biomass under anaerobic conditions, and this true carbon-negative method has attracted much attention as a means of converting plants to biochar and then incorporating it in the soil [4,5]. Biochar has been reported to be useful in many environmental applications such as carbon sequestration, climate change response, energy production, soil improvement, and waste management [6–8].

Barley straw is a good biomass for improving the physical properties of soil, but its incorporation into soil after a barley harvest can lead to an increase in organic acids and nitrogen starvation. This phenomenon occurs because the barley harvesting and rice transplanting periods are similar due to the characteristics of the cropping system in South Korea. Hence, the application of biochar derived from barley straw in terms of the efficient recycling of resources and environmental conservation is expected to be advantageous for the agricultural environment. Therefore, the objective of this study was to compare the effects of biochar and straw applications on rice yield and soil properties during a three-year period. The results obtained in this study can be applied to develop a biochar application method for use in a rice cultivation environment in the future.

2. Materials and Methods

The raw soil used in this study was a sandy loam with a bulk density of 1.31 Mg m^{-3}, porosity of 56.3%, pH of 5.87, and cation-exchange capacity (CEC) of 6.64 $cmol_c$ kg^{-1}.

Barley straw (BS) was used as the raw feedstock to produce barley straw biochar (BC). The furnace controller was programmed to drive the internal biomass chamber to a temperature of 400 °C at a rate of 3 °C min^{-1}, after which the peak temperature was sustained for 1 h. The pH, total nitrogen (TN), P_2O_5, K_2O, and CEC of the BC used in the experiment were 7.72, 0.42%, 0.30%, 1.41%, and 21.7 $cmol_c$ kg^{-1}, respectively; in addition, the BC mostly comprised C (>70%).

A field experiment was conducted to evaluate and compare the effects of the BC and BS applications on rice yield, soil properties, and GWP under paddy field conditions at Sepung-ri (34°56′33″ N, 127°33′56″ E), Gwangyang-eup, Gwangyang-si, Jeollanam-do, South Korea.

The field experiment was conducted during the rice cultivation seasons of 2015–2017. The three treatment conditions were: BC (2000 kg ha^{-1} of barley straw biochar), BS (2000 kg ha^{-1} of barley straw), and BC + BS (1000 kg ha^{-1} of barley straw biochar + 1000 kg ha^{-1} of barley straw, respectively). Each treatment area was separated by an untreated control (CN) area. BC was applied once in 2015, whereas BS was applied every year. In this study, no inorganic fertilizers were used during rice cultivation, and completely dried BC and BS were used. Water management in the paddy field was carried out through irrigation when rice was transplanted, and drainage was conducted 3 weeks before the rice harvest.

After rice harvesting, soil samples were collected from the surface layer (15 cm depth) using a soil sampler (auger) in each treatment area, and the samples were then air-dried and passed through a 2 mm mesh. Randomized soil samples were obtained from each plot, and a total of 15 soil samples were collected under each treatment condition. In this study, all soil analyses were performed using the methods described in NIAST [9].

3. Results and Discussion

The rice yields under each of the treatment conditions during the three-year study were significantly affected by the application type (Figure 1). Rice yields were significantly different among treatments, and the effect was particularly evident in 2017. During the study, rice yields for the CN, BC, BS, and BC + BS treatments ranged on average from 473 to 515, 497 to 532, 516 to 528, and 583 to 602 g m^{-2}, respectively. Among the treatments, the BC + BS treatment produced the highest average rice yield, which was stable during the three-year study. Under the BS treatment condition, rice yield tended to increase year by year, with the final yield (year 3) showing an increase of 2.4% from that in year 1. On the other hand, under the BC treatment condition, the rice yield tended to gradually decrease, and in 2017, the rice yield decreased by about 6.7% from that in 2015. In this regard, the application of a BC + BS mixture appears to be a very positive combination for maintaining stable rice production and soil quality. In the BC + BS treatment, rice productivity was maintained at 582.6–601.6 g m^{-2} during the three-year study, higher than that of the other treatments. The BC + BS treatment produced relative increases of 11.4–15.1% in 2015, 8.65–14.6% in 2016, and 13.9–27.1% in 2017 compared to those of the CN, BC, and BS treatments. The effect of increasing rice yield due to the BC application decreased in 2017, but the BS application resulted in a gradual increase in the rice yield. Considering these results, it seems that the advantages of BC and BS complement each other in the BC + BS treatment condition. It was shown that BS compensates for insufficient nutrients in BC, and BC retains nutrient elution by BS. These results agree with those in previous reports that the application of BC combined with additional nutrients can increase the overall nutrient availability of agricultural soil [6,10,11]. Therefore, our results indicate that the positive effect of the BC + BS application on rice productivity was the result of an improvement in the quality of soil over the three-year rice cultivation period, although some differences were seen depending on treatment conditions.

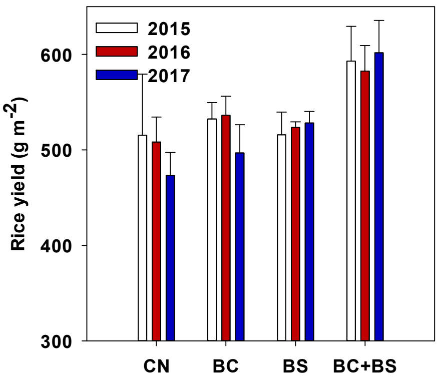

Figure 1. Changes in rice yield from each of the tested areas.

Table 1 shows the changes in soil physicochemical properties following the biochar and straw treatments and after the final rice harvesting. The range of soil-property values after rice harvesting were as follows: soil bulk density between 1.25 and 1.33 Mg m^{-3}, pH between 5.78 and 5.96, EC between 0.18 and 0.20 dS m^{-1}, SOC content between 9.04 and 10.4 g kg^{-1}, TN content between 1.39 and 1.69 g kg^{-1}, Avail. P_2O_5 content between 55.5 and 60.0 mg kg^{-1}, and CEC between 6.25 and 6.80 $cmol_c$ kg^{-1}. The soil changes after the final rice harvesting were different in the BC and BS application areas. Soil bulk density and pH were improved in all treatments except for the CN treatment compared to those of the raw soil. The SOC and TN contents after the BC application increased by 0.56 and 0.08 g kg^{-1}, respectively, compared to those of the CN soil, while those after the BS and BC + BS applications increased by 0.89–1.36 and 0.16–0.3 g kg^{-1}, respectively. The soil CEC values after the BC, BS, and BC + BS treatments were 0.55, 0.37, and 0.49 $cmol_c$ kg^{-1} higher than those in the CN, respectively.

Table 1. Soil properties of experimental treatment sites after rice harvesting.

Treatment	Bulk Density	pH	EC	SOC	TN	Avail. P_2O_5	CEC
	($Mg\ m^{-3}$)	($1{:}5H_2O$)	($dS\ m^{-1}$)	($g\ kg^{-1}$)		($mg\ kg^{-1}$)	($cmol_c\ kg^{-1}$)
CN	1.33 b [1]	5.78 a	0.18 a	9.04 a	1.39 a	56.5 ab	6.25 a
BC	1.26 a	5.94 b	0.19 bc	9.60 ab	1.47 b	55.5 a	6.80 b
BS	1.25 a	5.93 b	0.18 ab	10.4 b	1.69 d	58.6 ab	6.62 ab
BC + BS	1.26 a	5.96 b	0.20 c	9.93 ab	1.55 c	60.0 b	6.74 b

[1] Different letters within the same column indicate significant differences, as determined by Tukey's test with $p < 0.05$.

The correlation among rice yield and the major soil characteristics in the study's paddy field during the three-year study are shown in Figure 2. The results demonstrate the synergy between BC and BS, the combination of which resulted in the most increasing rice productivity among all treatments during the three years, as illustrated by the results obtained through the application of BC and the appropriate application of BS.

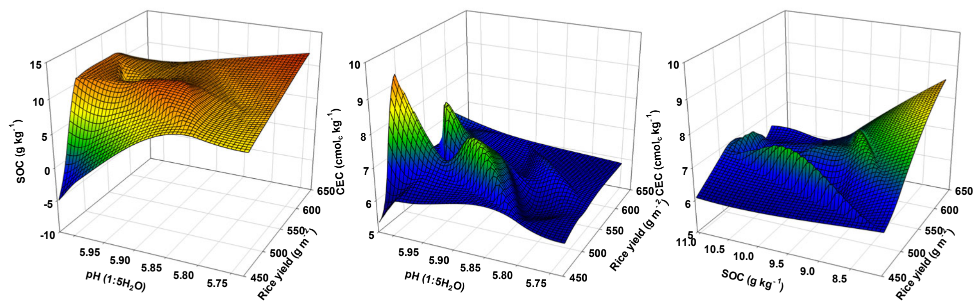

Figure 2. Correlations among rice yield and major soil characteristics.

4. Conclusions

Based on our results, the utilization of BC and BS in rice paddy fields is effective in maintaining or increasing soil quality and the rice crop growth capacity of rice paddy soils. The single BC-alone application had a disadvantage in that it resulted in inconsistent rice production, but a combination of a single BC treatment and annual BS supplementation produced the greatest increase in rice yield. Therefore, considering the other benefits of BC and BS applications such as improved soil quality and the replacement of the use of inorganic fertilization, we recommend using a combined application of BC and BS. Such an approach can reduce the application of inorganic fertilizer, thereby encouraging the development of sustainable organic agriculture.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/IOCAG2022-12244/s1, Poster: Effect of Soil Amendments Derived from Agricultural Biomass on Rice Yield and Soil Fertility in a Paddy Field of South Korea.

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